Viktor Kaplan and the Adjustable-Blade Propeller Turbine

The variable geometry turbine invented by Austrian engineer, Dr. Viktor Kaplan is used today in plants that operate run-of-river, or where a wide range of operating flexibility is needed. Here's the story of the development and commercialization of this sophisticated machine.

By Robert W. Shortridge

The two earlier articles in this series described the development of the Francis turbine and the Pelton wheel.[1,2] Both devices were developed in the United States; the first by a native of England who came to the United States as a youth, and the second by an Ohio-born American. Both Francis and Pelton were largely self-educated. In contrast, the Kaplan turbine was a European development. Its inventor, Viktor Kaplan, was an Austrian with an earned doctorate in engineering from the Polytechnic University of Vienna. Kaplan spent most of his career in the academic world at the Polytechnic University of Brunn, Austria (now Brno, Czechoslovakia).

Kaplan's Education and Early Works

Born in Murzzuschlag, Austria in 1876, Viktor Kaplan was educated in Vienna. He received a mechanical engineering diploma from the Vienna Polytechnic University in 1900. After a year in the navy and two years designing and building diesel engines for an engine works, he went to the Brunn Polytechnic University in 1903 as professor of mechanical engineering, kinematics, and the science of machine construction. He almost immediately began work on hydraulic turbine design and construction; his first publication in this field, in 1905, was on the design and construction of Francis turbine blades.

Kaplan published his first major work in 1908—a book on the scientific design and construction of the Francis turbine rotor. He presented this book to the Vienna Polytechnic University as his doctoral dissertation and received his doctorate in 1909. At the same time, he became assistant professor of water power machines at the Brunn Polytechnic University, and immediately busied himself in setting up a laboratory for the study of hydraulic turbines.

Between 1908 and 1911, along with colleagues Mieses and Hamel of the Brunn Polytechnic University, Kaplan performed theoretical studies on multidimensional fluid flow. These studies progressed to experimental work on a small scale using a copper-alloy runner just four inches in diameter. The model operated in a glass casing so that fluid-flow characteristics could be observed. The head under which this small turbine operated was only 19 inches; even so, its runner showed very high specific speeds, which ranged between 500 and 900.

The First Patents

The first of what would eventually be some 260 Kaplan patents throughout the world was Austrian patent 74,388, issued December 28, 1912. This patent covered a turbine which retained the adjustable wicket gates of the Francis turbine and the radial flow pattern through those gates, but which placed the runner blades wholly below the level of the wicket gates. The runner blades themselves had a width less than the pitch from one blade to the next, so that there was no overlap between adjacent blades. Predominantly axial flow through the blades occurred with this arrangement, rather than the radial or mixed flow typical of the Francis turbine.

The basic patent underlying what we now know as the Kaplan turbine was Austrian patent 74,244, issued August 7, 1913. This patent covered a turbine machine with runner blades the pitch of which could be varied during operation. The corresponding application for U.S. patent was filed July 30, 1914, but was not issued until September 8, 1931, as U.S. patent 1,822,778[3]. The primary claim of this patent was for "a runner wheel for high speed water turbines provided with guide vanes, said wheel comprising a plurality of angularly adjustable blades, and means to adjust said blades while the wheel is running so as to vary not only the outlet angles and passages but also the inlet angles and passages of the wheel, to correspond to variation in the supply of water and in the power required." Ten additional U.S. patents were awarded to Kaplan during the period from 1921 to 1924. These covered various aspects of turbine runners, guide vanes, and

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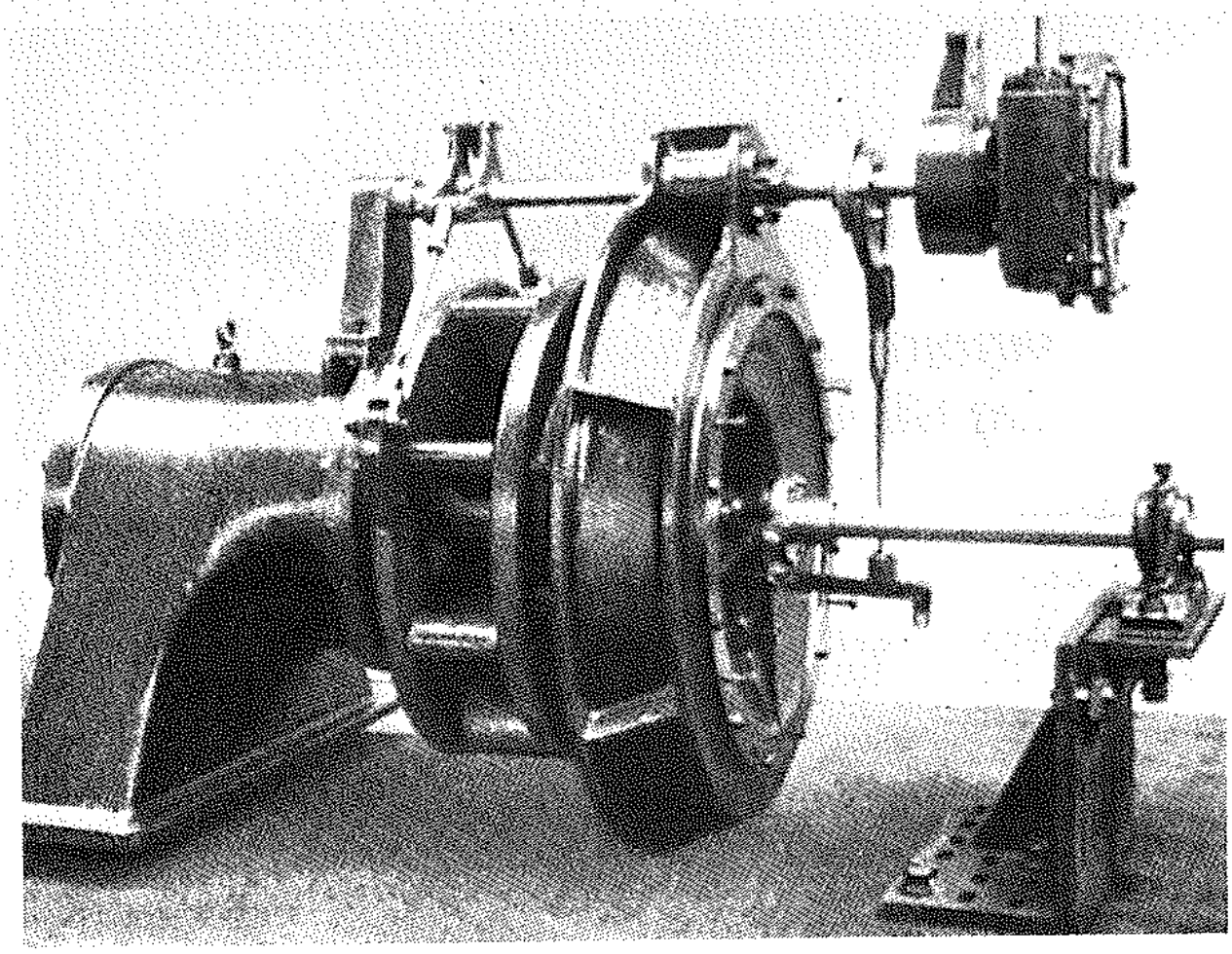


The first commercial Kaplan turbine which went in service in 1919 at a braid and wool yarn manufacturing plant. The machine produced 25.8 horsepower under 2.33 meters of head at an efficiency of 84 percent.

draft tubes.

The Kaplan Turbine in Operation

It was not until the last year of World War I (1918) that Kaplan found a customer and a fabricator for his first commercial-size turbine. The customer was a braid and wool yarn manufacturer, Hofbauer Wwe., located in Velm, a small town near Vienna. The steelworks of Ignaz Storek, in Brunn, was the fabricator. Storek previously worked closely with Kaplan, providing experimental facilities and fabricating the four-inch experimental runner that Kaplan tested in 1910 prior to his first patent application.

The Kaplan turbine at the Hofbauer establishment was tested in 1919. With a runner diameter of 24 inches and a head of nine feet, it developed 35 horsepower at 480 rpm, with a discharge of 286 gallons per second.

Other early Kaplan installations included turbines at Podebrady, Czechoslovakia in 1921, and at Gorizia, Italy and Kromertz, Czechoslovakia in 1924. The Podebrady turbine had a 71-inch runner and developed 275 horsepower at heads ranging from 4 1/2 to 7 1/2 feet. The Kromertz turbines had 87-inch runners and each developed 1,000 horsepower under a 14 1/2 foot head, running at 214 rpm with a discharge of 6,000 gallons per second.

There was interest in the Kaplan turbine in Sweden as early as 1913, but World War I interfered, and the project was not taken up again until 1921. By that time, American manufacturers had done quite a bit of work on fixed-blade propeller turbines, but their efficiency was not deemed suitable for Swedish requirements for high efficiency over a wide range of loads.

In 1921 Sweden's largest turbine manufacturer, Werkstaden, renewed their interrupted study of the Kaplan turbine. It was found that fixed-blade turbines built according to Kaplan's 1912 patent had distinctly higher efficiency than American propeller turbines, but that this high efficiency was attained only over a narrow range of load. The company then worked to design a hub structure and mechanism for the movable-vane Kaplan turbine runner that would be strong enough to withstand the stresses involved in changing the pitch of the vanes during full-scale operation. Testing was successful, and by 1923 Werkstaden had built and installed several movable-vane Kaplan turbines in Sweden. At one such installation (Stromsberg), an efficiency of 88.2 percent was measured at normal head of 13.8 feet. Efficiency remained above 80 percent at horsepower outputs varying between 190 and 465.

The Werkstaden people went on to build and install, in 1925, what was then the largest Kaplan turbine in the world. This was at Lilla Edet, in southern Sweden. This turbine had a four-bladed runner 19 feet in diameter. It operated at 62.5 rpm under a normal head of 21.3 feet, and developed 11,200 horsepower. Efficiency at this power level was guaranteed to be 86 to 87 percent and was measured at 89 percent. Overloaded to the point of developing 19,000 horsepower, or at part-load and developing only 4,000 horsepower, its efficiency remained above 75 per cent.

Competition

Many other versions of propeller turbines were manufactured in competition with the Kaplan turbine during the 1920s. In Europe two Scandinavian manufacturers developed the Lawaczeck runner, which bore a resemblance to a centrifugal pump impeller. In the Lawaczeck turbine, incoming water passes through wicket gates which impart a swirling motion, then through an annular, somewhat restricted passage which increases its forward velocity, and finally to the fixed runner blades, which are shaped so as to accept the water's rotary component of motion without shock or turbulence and discharge the water completely without rotary motion. The Lawaczeck turbine is designed for best efficiency with wholly axial discharge; it decreases rapidly in efficiency with decreasing load. For a short period of time it was popular to team Lawaczeck turbines with Kaplan turbines, letting the former handle a constant base load and the latter the varying peak loads.

Other European companies manufacturing propeller turbines of their own design during this period were Escher Wyss in Zurich, J.M. Voith, Vevey Machine, and Storek in Brunn.

U.S. Development

In the United States, the general attitude of hydraulic engineers during the '20s was that the presumed complex mechanism necessary to adjust the blade angle in the Kaplan turbine was not rugged and trouble-free enough to meet U.S. standards of performance and durability. However, the rapidly growing number of Kaplan

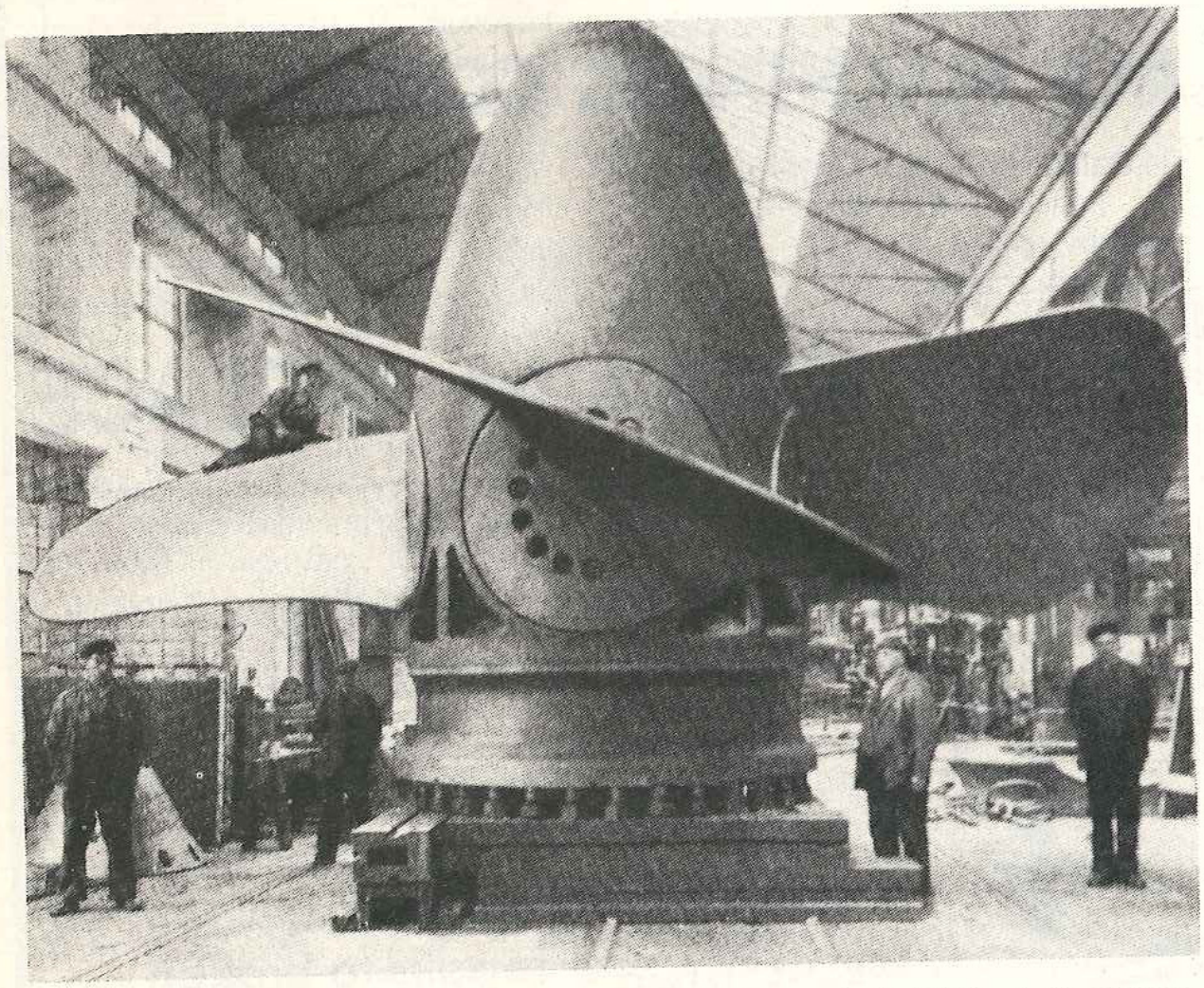
installations in Europe challenged this assumption. By 1929, at least 150 Kaplan turbines were operating in Europe, with a total capacity of more than 300,000 horsepower. Their economical use of water at heads of less than 50 feet was noteworthy, as was the fact that they could carry overloads of some 50 percent without significant loss of efficiency.

A 1929 ASME paper noted that Kaplan turbines were perhaps 15 to 75 percent more expensive than fixed-blade propeller turbines of comparable output.[4] They were also more complicated and consumed more oil. It was pointed out, however, that these disadvantages were usually outweighed by savings in water and generator costs. The author of the paper concluded that the Kaplan turbine would appear in the U.S. before long.

Another reason for the delay in American adoption of the Kaplan turbine was the Nagler propeller turbine, which was developed in the U.S. at the same time the Kaplan turbine was developed in Austria. As larger and larger Francis turbines were put into service in the early 1900s, their rotational speed decreased, also decreasing efficiency of the generators connected to them. Forrest Nagler, an American engineer, recognized the need for a higher-speed turbine to operate under low heads, and the consequent need for a low-friction design. His thought was to reduce the wetted surface of the runner to a minimum, and thus reduce water friction in the turbine. Nagler first removed the band of the runner to eliminate water friction on it. He then made the runner blades radial and reduced their size and number to a point where their projected cross-sectional area was less than the cross-sectional area of their passage. He ended up with a propeller runner having wicket gates and a whirl chamber upstream from it.

The Nagler propeller turbine proved to give about twice the speed of rotation of a Francis turbine under equivalent conditions of head and power output. The first commercial installation of the Nagler turbine was in 1916, and many other commercial installations followed it.

Like the first Kaplan turbine, the Nagler turbine originally had fixed blades. Both turbines attained highest efficiency at essentially full power output, and lost efficiency rapidly as their loads decreased. Kaplan solved this problem by providing a means for simultaneous adjustment of the turbine blade angle and that of the wicket gates by means of a governor and hydraulic servomotor. Both wicket gate angle and turbine blade angle were thus automatically adjustable during operation for optimum efficiency under wide variations of load. Nagler, recognizing the need for such adjustment for varying loads, provided a means for *manual* adjustment of the turbine blades in some of his later turbines. The available literature does not indicate whether Nagler felt constrained by Kaplan's European patent situation or whether he felt that the Kaplan mechanism was too complex and apt to fail in use.



Propeller assembly, 8 meters in diameter, built in the late 1920s for installation in the Vargon, Sweden, Power Station. Hundreds of similar Kaplan turbines are in service today.

The first Kaplan turbine in the United States was installed in early 1929 at the Lake Walk plant of the Central Power & Light Company of San Antonio. Lake Walk is on Devil's River near Del Rio, Texas. The turbine installed was a unit developing 1,900 horsepower under a head of 33 feet, directly driving a 1,500-kVA generator at 277 rpm. All equipment, both hydraulic and electrical, was fully automatic, and operated without station attendants. During the first year of operation, Devil's River had extremely low and irregular flow. As a consequence, another plant 4 1/2 miles upstream (using fixed blade runner equipment) was able to run only 12 to 15 hours a day at a load that yielded its highest efficiency. In contrast, the Lake Walk Kaplan turbine and generator operated continuously during the same period at high efficiency despite the extreme flow variations. It was estimated that the output of the Lake Walk plant during this period was 10 to 12 percent higher than it would have been if a fixed-blade runner had been used and operated under the same conditions of low and variable flow. In its second full year of operation, the Kaplan turbine at Lake Walk operated 97 per cent of the total time without any shutdown for maintenance.

Later in 1929, Wisconsin Power & Light built a hydroelectric plant on the Rock River at Rockton, Illinois, near Beloit, Wisconsin. It utilized a fixed-blade turbine developing 730 horsepower at 100 rpm under 10 1/2 feet of head, and a Kaplan turbine which developed 980 horsepower at the same speed and under the same head. The plant was fully automatic and was controlled from the load dispatcher's office in Beloit. In this plant, the fixed-blade unit operated only at its point of highest efficiency, while the Kaplan turbine operated under all

conditions of stream flow. Flambeau Paper, of Park Falls, Wisconsin, installed a similar two-turbine plant in late 1930, with one fixed-blade unit and one Kaplan unit.

About the same time, Utilities Power & Light placed two Kaplan turbines (each developing 2,100 horsepower under 40-foot head at 327 rpm) in its Niangua River plant near Lebanon, Missouri. Field tests of these units showed an efficiency of more than 90 percent for each turbine, with power outputs ranging from 650 to 1,500 horsepower—more than 84 percent over the range of 375 to 2125 horsepower. The 40-foot head was considered the maximum usable head for the units' four-blade propellers to avoid cavitation and excessive vibration; laboratory tests indicated that any higher heads would require the use of five-blade propellers.

While the Kaplan turbine saw extensive use in Europe by the late 1920s—and was making these and other inroads into United States hydroelectric practice—an American engineer, R.W. Terry, began development of a type of propeller turbine which for a time promised to become a worthy competitor to the Kaplan turbine. Terry, fully cognizant of the advantages gained by the governor-adjustable blades of the Kaplan turbine, visualized what he hoped would be a further improvement in adjustable blading. During the early 1930s, Terry developed and patented a runner whose blades were pivoted with reference to their center of pressure so that they would be self-adjusting. They set themselves at the most efficient angle for constant-speed operation for each condition of gate-opening and head.

The first commercial installation of the Terry turbine was a resounding success. Despite a scale-up from the laboratory test model of 115 times in water-passage area and 300 times in power output, a Terry runner of almost 15 feet in diameter at the Kanawha Valley Power Company near Charleston, West Virginia, consistently developed about 8,500 horsepower under 23 feet of head, as compared to an otherwise identical fixed-blade turbine rated at 6,600 horsepower. Kanawha Valley installed two more Terry turbines later in the 1930s. In 1940, two more Terry turbines (rated at 10,000 horsepower each at 200 rpm under 61 feet of head) were put into place at the Austin Dam site of the Lower Colorado River Authority. These latter turbines were field-tested and showed 92 per cent efficiency.

Despite the apparently successful commercial-scale use of the Terry turbine, the hydroelectric industry in general seemed to prefer the Kaplan turbine, with its positive hydraulic control over blade angle. By the 1950s, Terry's own company, Newport News Shipbuilding and Dry Dock Company, began to manufacture turbines of the Kaplan type.

The first really large-scale United States project using Kaplan turbines was at Safe Harbor, Pennsylvania, on the Susquehanna River. In 1932 six turbines were installed, each with a 220-inch five-blade runner which would deliver 42,000 horsepower at 100 rpm for 25 Hz. electricity, or 109.1 rpm for 60 Hz., under a head of 55 feet.

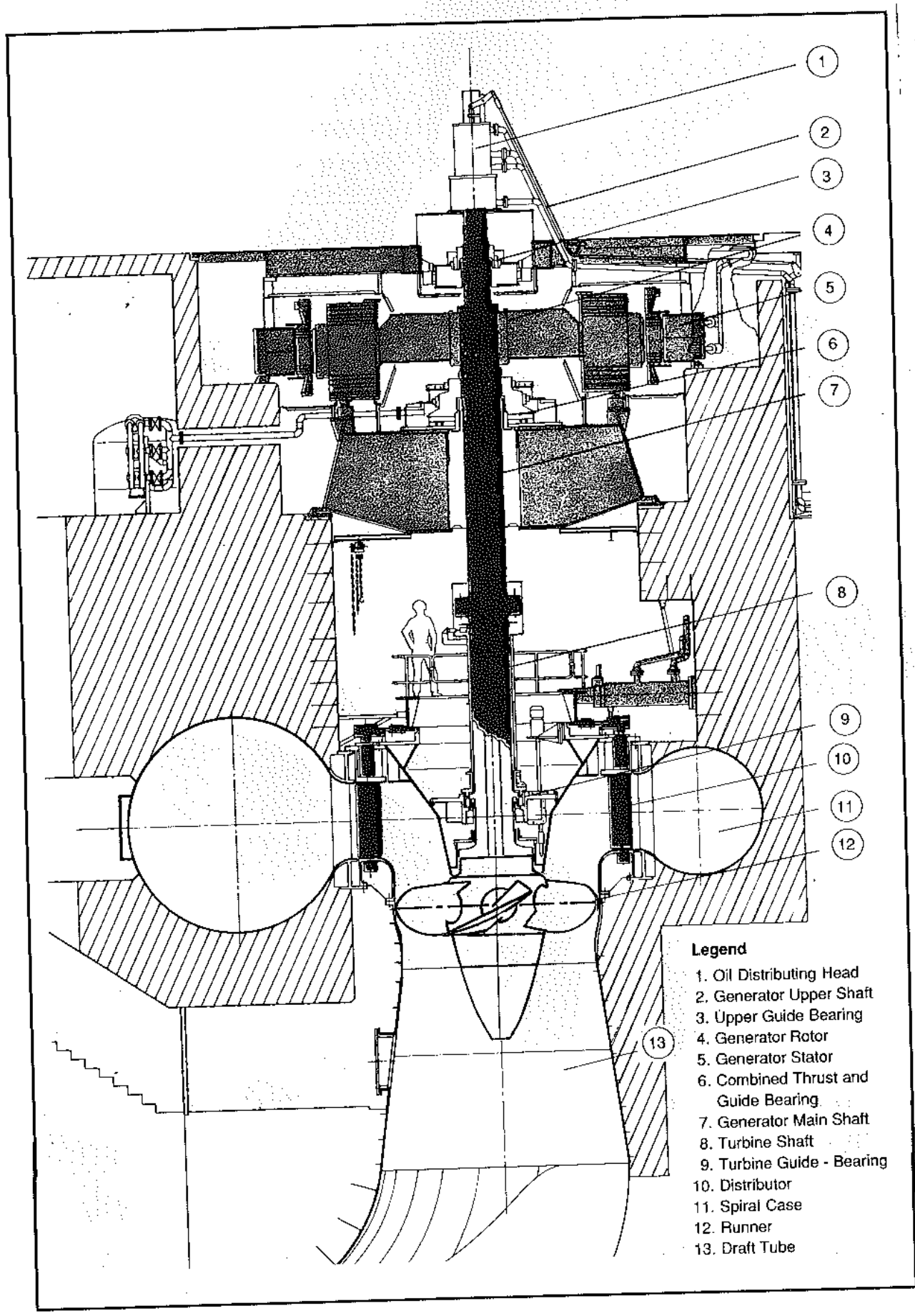


Figure 1: Cross section of a vertical Kaplan turbine shows the components typical of this type of machine. (Courtesy of IMPSA International, Inc.)

Later Developments

In subsequent years, further major developments in Kaplan turbines have been many. By the 1950s these turbines grew greatly in size, as

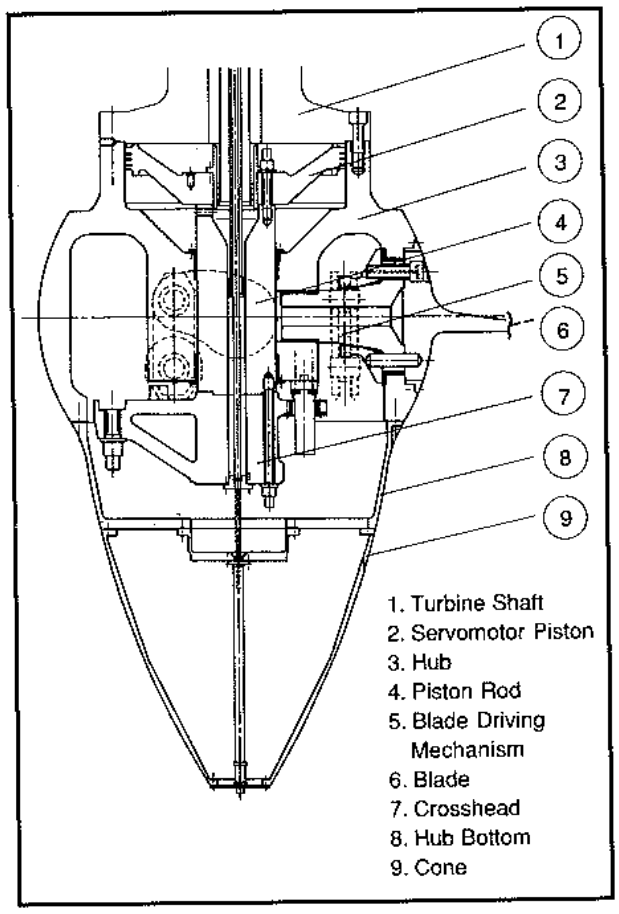


Figure 2: Cross section of a Kaplan runner hub, showing internal blade adjusting mechanism. (Courtesy of IMPSA International, Inc.)

exemplified by the 143,000-horsepower, 90-rpm, 89-foot-head turbines at Ice Harbor on the Snake River in Washington. Operation under far higher heads—as high as 200 feet in Europe—without excessive cavitation damage became possible by means of more precise design and machining of the blades and their facing with materials which resist pitting. Tubular and bulb turbines, invented in the United States but developed mostly in Europe, became popular in situations involving low-head, relatively low-power installations. These situations included run-of-river and tidal-power installations.

A 1988 paper surveyed more than 60 vertical Kaplan turbine installations that were designed between 1975 and 1985 and installed worldwide.[5] Their outputs ranged from five to 120 MW, and their operating heads from 10 to 200 feet. The survey showed that the advantages of the Kaplan turbines over Francis turbines lie in their suitability for run-of-river plants, for plants where the operating head varies greatly, and where electrical generation requires great operational flexibility. Kaplan turbines are mechanically more complicated, but their high efficiency over a wide range of gate openings and heads makes up for this complexity in many situations. Cavitation problems in Kaplan turbines—generally involving the throat ring and the periphery of the runner blades—are often difficult to repair, involving substantial dismantling to get at the pitted areas.

Cross sections of a typical, modern Kaplan turbine and runner hub are shown in Figures 1 and 2.

Kaplan's Later Years

Viktor Kaplan, in ill health, retired in 1931 at the age of 55. His biographers cite various reasons for the ill health, ranging from the long hours of work in his basement hydraulic laboratory as a young man, World War I privations, and the strain of protecting his many patents against infringement. In 1932 the Society of Austrian Engineers and Architects presented him with its highest honor, the gold medal of the society. Kaplan died suddenly on August 23, 1934, his place in hydraulic engineering history secure and his name used to denote a specific type of turbine. □

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Notes:

[1] Shortridge, R.W., "Francis and His Turbine," *Hydro Review*, February, 1989, p. 24.

[2] Shortridge, Robert W., "Lester Pelton and His Water Wheel," *Hydro Review*, October, 1989, p. 22.

[3] Kaplan, Victor, Hydraulic turbine, U.S. Patent 1,822,778, filed July 30, 1914, granted September 8, 1931. *Official Gazette,* September 8, 1931, p. 517.

[4] Van Leer, B.R., "Some Interesting European Hydraulic Turbine Research," *Transactions of the ASME,* HYD-51-6, pp. 57-66, 1929.

[5] Lugaresi, A., and A. Massa, "Kaplan Turbines: Design Trends in the Last Decade," *Water Power & Dam Construction,* May 1988, pp. 12-17.

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